Multiple Degree-of-Freedom Input Devices and Displays for Virtual Reality in Protein Visualization

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Introduction

A large number of input devices, some in 2D, some in 3D, and display devices exist, which are commonly used for the exploration of large-scale 3D data structures. Unfortunately, not all combinations of input and display devices work together in a suitable and useful manner, either because they are not capable of 3D input or because, for instance, they need a hard table surface to work properly, making them impractible, for example, for use in a large-screen, stereoscopic environment, where user immersion and freedom of motion in the display space are required.

The purpose of this study is to provide an overview of existing technology and to identify combinations of input and display devices that have proven to work well together. The survey identifies features and limitations of each technology and explains why some input devices, even though they have, for instance, sufficient degrees of freedom, are not suitable for accomplishing a certain task, or how they can be replaced with other devices that may be more suitable or that make solving the given task more efficient.

In addition to the survey, a case study on protein visualization has been conducted. The application has been chosen because it incorporates complex navigational tasks, requires six degrees-of-freedom user input, and gains from 3D stereoscopic visualization on a large, high-resolution display system. These requirements are typical for many scientific visualization applications as well as for games, the latter being the driving industry for the development of cost-efficient VR solutions.

Related Work

Virtual input devices for 3D interaction were first classified by [He and Kaufman 1993]. An attempt to formalize the design, evaluation, and application of interaction techniques for immersive environments was made by [Bowman and Hodges 1999], while a taxonomy for the design of 3D interfaces was compiled by [Gabbard 1997].

Techniques for bi-manual control of two independent cursors [Zeleznik et al. 1997] might be necessary for collaborative or bi-manual interaction, which is supported by PINCH gloves as input devices. Applications for PINCH gloves for the Responsive Workbench (RWB) were first explored by [Krüger and Fröhlich 1994], [Cutler et al. 1997], and [Obeysekare et al. 1996].

Single-screen projection based systems include the Responsive Workbench (RWB) [Krüger and Fröhlich 1994], the ImmersaDesk, PowerWalls and Infinity Walls [Czernuszenko et al. 1997]. The CAVE was the first multi-screen systems for large VEs which provides total immersion[Cruz-Neira et al. 1993]. Higher resolutions are supported by display walls for multiple projectors [Schikore et al. 2000] and tiled displays [Humphreys and Hanrahan 1999].

Rudimentary molecule structures have been previously explored in VEs by [Obeysekare et al. 1996] and [Akkiraju et al. 1996]. In recent years, data sets of the 3D structure of macromolecules have been collected in the Protein Data Bank [Berman et al. 2000]. Kinemage [Richardson and Richardson 1992], RasMol [Sayle and Milner-White 1995], VMD [Humphrey et al. 1996], PyMOL [DeLano 1998-2004], and MolScript [Kraulis 1991] are software packages for molecule visualization. Most of these applications focus on the visualization of a single molecular structure with traditional mouse and keyboard interaction. We added new modules to MolScript, which is commonly used to generate high-quality visualizations for print publications, and enhanced the program with VR interaction support and options for comparative exploration of several macromolecule datasets in a variety of virtual environments (VEs) in real time.

Multiple Degree-of-Freedom Input Devices for VR

In many VR applications, the software is required to facilitate multiple degree-of-freedom user interaction. Six degrees of freedom (6dof) are commonly used to implement this. Sensors or controls usually provide information on the position and orientation of the tracker in 3D space, where the position is given by the x, y, and z coordinates and where angles for pitch (rotation about x axis - horizontal), yaw (rotation about y axis - vertical), and roll (about z axis - forward) specify the orientation. Not all applications incorporate all six degrees of freedom, and therefore input devices with less degrees of freedom might be more appropriate for the specific task.

Stylus

The simplest 6dof input device is probably the stylus. An electromagnetic tracking system provides the desired information about position and orientation and sends it back to the software application. Even VR-unexperienced users intuitively hold and use a stylus like a pen or laserpointer, and are able to pick a virtual object by pressing a single button on the stylus with the index finger. The handling in terms of general finger position and movement is similar to the mouse. The small tip of the stylus is tracked, eliminating in most cases the need for a cursor, i.e. the virtual object can usually be 'touched', picked and dragged directly with the device.

PINCH Gloves

Data gloves in general provide the user with an intuitive device for more sophisticated picking operations, and, with certain limitations, quasi gesture recognition. Some data gloves feature resistance strain gauges for each finger. More basic types simply have metal contacts mounted at every finger tip, allowing for simple pinch gestures. Basic and intuitive pinch gestures are used for interaction metaphors like "grab and move" and "grab and rotate". A tracker is usually mounted on the backside of the cloth gloves, which results in a variable offset between the fingertips which grab the virtual object and the tracker location. This may cause actual objects to be occluded by the hand, making the use of a virtual cursor necessary if precise navigation is required. If a grabbed object is moved or rotated, the center of rotation is usually the wrist of the grabbing hand. However, most applications use the tracker location instead of the wrist, causing a slight discrepancy between the pivotal wrist point and the actual tracker position as the center of rotation. Some limitations are given by the noteworthy fact that PINCH gloves only come in one size and are usually not washable. PINCH gloves are very suitable both in a tabletop and in a desktop environment, i.e. for use with virtual workbenches or smaller single screen displays, which enable interaction with objects "in arms reach", but also for large-screen projection systems, provided that the wires that are usually attached to the trackers do not limit users in their freedom of movement. Some wireless solutions are currently under development, but none of the existing systems implemented so far has a range to cover the large volume, for example, of a CAVE-type system. It should be mentioned that even though a large number of pinch combinations is theoretically possible, only a limited number is ergonomically feasible, and the utilization of too many different pinch combinations or unnatural gestures in an applications has shown to confuse the user.

Mouse

Mice and trackballs are great for interaction in 2D desktop environments, where drag'n'drop and click'n'rotate are common interaction metaphors. Since only one hand is needed to move the mouse in 2D and to press the three mousebuttons, the second hand can be used for operating the keyboard and for activating additional functions like zooming in z via keyboard modifiers. Due to the limitations of 2D input devices, and as we will later see, also of 3D input devices, often an additional button must be pressed on the device or on the keyboard to switch between different axes or degrees of freedom. Another common phenomenon is the fact that many input devices employ an indirect mode of navigation, i.e. the user looks at the screen, not at the device, and navigates the mouse cursor on screen by moving the mouse. Most people adopt their hand-eye coordination quickly to this paradigm. It is important to note, however, that this separation of hand movement and visual feedback seems to be much more difficult to adapt to in a 3D virtual environment. Preliminary studies have shown that most people find it more intuitive if they can interact directly with the object rather than using an indirect method.

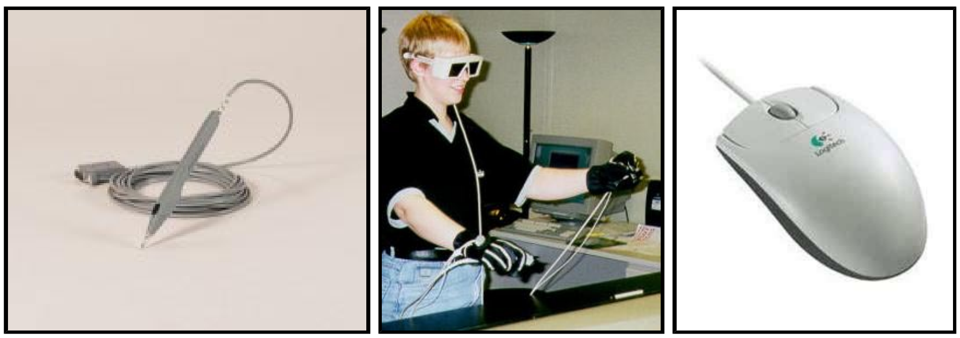

Figure 1: (a) Stylus, (b) PINCH gloves, and (c) mouse.

Joystick

A joystick is a common input device for 2D navigation. One hand holds the stick for 2D movement, while the buttons on top of the stick can be pressed by thumb and index finger. Some joystick models also allow to turn the stick, thereby adding an additional rotation axis. The joystick base has to be mounted on a table or held by the second hand, which is also needed to reach additional buttons and throttles on the base. In general, the capabilities of a joystick are very similar to those of a 2D mouse. Two out of three translation directions (x, y, and z) can be selected and mapped to the joystick movement. The selected two directions can be changed by holding down a button on the joystick or on the keyboard (e.g. the SHIFT key). Equivalent movement for two out of three additional degrees of freedom (yaw, pitch, and roll) can be activated via pressing an additional button.
The Microsoft SideWinder Force Feedback Pro joystick was used as a reference. Due to its weight and the force feedback functionality, it has to be mounted on a table. The base of this model provides five buttons and a throttle, while the stick features one button for the index finger and three buttons plus a mini joystick for the thumb. The stick axis can be rotated for an additional degree of freedom. Note that this specific joystick is designed for right handed use.

Nintendo64 Controller

A modified Nintendo64 controller was used as a flexible wand for a CAVE-like environment. The tracker is mounted to the end of the wand, opposite to the wrist. A trigger (1D axis) can be pressed and released by the index finger, while the other buttons on the handle can be reached by the thumb of the same hand. To move the jog shuttle (1D axis) and its buttons, a second hand is needed. If they are not used in the application, single-handed interaction is possible. Due to the design of the device and the layout of the buttons, the use of four buttons for various program functions turned out to be already confusing to some users. The design of the device can be compared to a VCR remote control, which is reflected in the way users hold and handle the wand. Similar to a remote control, the wand is usually pointed in the direction of the screen and the VR object. Common navigation modes include the before mentioned ones for pinch gloves and stylus as well as a global navigation mode, where the world location is translated according to the trigger orientation in the direction of the wand position, or rotated according to the jog shuttle.

Gamepad

Gamepads provide multiple degrees of freedom. They come either wired or with a convenient cordless option. Most gamepads feature up to two analog and one digital joysticks plus sliders, thereby providing several axis for numerous DOFs. Four or more buttons are usually located on top of the device so that they can be reached by the thumb during interaction, while four buttons are on the front of the device within reach of the index and middle fingers. The joysticks are moved with the thumbs. A gamepad is similar to the joystick in terms of programmibility and functionality. In both cases, two out of three degrees of freedom must be chosen to be mapped onto input devices that are 2D in nature (joystick, 2D digital pads). Due to their design and weight, both hands are needed to hold the device. Cordless gamepads need batteries which add to the weight of the device. The weight also increases if motors for rumble and force feedback functions are integrated in the wings. While steering wheels and some joysticks are too heavy to hold during interaction with the virtual world, the weight of the gamepad is adequate and not hindering. Some wands, including the Nintendo64 wand, can weigh as much as devices in the gamepad category. We used a Logitech© WingMan® Cordless Rumblepad (USB) with 7 axes and 10 programmable buttons for our studies. The navigation can easily be adapted to the habits and preferences of the user, since it is very easy to map a variety of navigation modes and keyboard functions to the interaction device.

Steering Wheel

We used the Microsoft SideWinder Force Feedback Wheel (USB) as a reference. Due to its size, weight, and design, the steering wheel itself has to be mounted on a table, while the two pedals are usually placed on the floor underneath the table, resulting in a cockpit layout, which enhances the perception of the driving experience associated with this specific device. While the steering wheel can be used by one hand, two handed use is advised for exact control and for applications which employ force feedback. Since several buttons are located on the front and on the back of the wheel, both hands have to grip the wheel to reach all buttons. The two pedals provide a second axis to the steering wheel axis, but need to be operated by one or two feet. While the pedals could theoretically be operated by a second user, this is not recommended since it often results in awkward and non intuitive interaction. Steering wheels are usually only employed by applications which feature a driving metaphor, where the camera moves and no object has to be grabbed or manipulated. Navigating the virtual world like this is intuitive for exploration tasks of large virtual environments and worlds, but it is not suitable for VR-based space or desktop metaphors where the main focus is on object exploration and manipulation.

Figure 2: (a) Microsoft SideWinder Force Feedback Pro joystick, (b) a modified Nintendo64 controller, (c) the Logitech© WingMan® Cordless Rumblepad (USB) gamepad, and (d) the Microsoft SideWinder Force Feedback Wheel (USB).

PHANTOM Omni

The PHANTOM Omni device by SensAble Technologies, Inc., is a compact force feedback device, which is mounted to a table top. The user moves a stylus, while the position and orientation of the stylus are tracked. The handling is similar to the stylus. In addition to position and orientation tracking, the device also provides force feedback to the user. The range of motion is limited to the hand movement pivoting at the wrist. Due to the very limited motion range, the device is not suitable for intuitive interaction in large immersive environments with large projection displays, but very useful in connection with smaller desktop VR environments.

Figure 3: The PHANTOM Omni device by SensAble Technologies, Inc.

Preliminary Conclusions

In summary, we found that current input devices have the following features and limitations:

- Most 2D input devices are of very limited use when incorporated in a 3D virtual environment. Typical workarounds, such as pushing a button on the device or a modifyer key on the keyboard are usually cumbersome and not very intuitive.
- Current 3D or multiple-degree-of-freedom input devices, such as gamepads, are often a collection of 2D input devices (joysticks, 2D digital pads, etc.). We found two reasons for this:
  (a) Lack of better technology (real 3D input), and
  (b) Convenience for the user (Most users have already adapted to the 2D control [plus modifyer key] paradigm and have learned to operate more than one 2D control at a time.)
- The discrepancy between hand motion and visual feedback (hand-eye coordination) seems to work well in a 2D environment, but requires a much harder learning process in 3D and therefore should be avoided.
- 3D input devices should be wireless and not mounted to a table to enable the user to roam about freely in a 3D virtual environment.

Displays

A virtual environment (VE) is characterized by the display mode and the visualized information. Monoscopic and stereoscopic rendering provide a virtual depth perception to immerse the viewer in a virtual world. The degree of immersion depends on the projection type and nature of the information which is supposed to be visualized. In general, a large display size allows several users to collaboratively investigate virtual models.

Multi-screen Projection-based Systems

The CAVE is a multiple-screen projection-based virtual reality system with four to six screens that are arranged in a cube for total immersion. The most common setup consists of three walls and a floor. The major advantage of the CAVE is the fact that it enables collaborative exploration of several large-scale objects through manipulation and navigation within an immersive virtual world. The viewer navigates the virtual scene by naturally moving around inside the cube, while his field of vision is completely covered by the images. The virtual models can be out of reach for the user, so that the object or the virtual world has to be moved towards the user, or the user has to walk closer to the examined detail. Spatially Immersive Displays (SIDs) like the CAVE enable simultaneous access to a greater amount of information than any other display devices and help escaping the bias towards 2D computing by organizing objects more effectively in 3D.

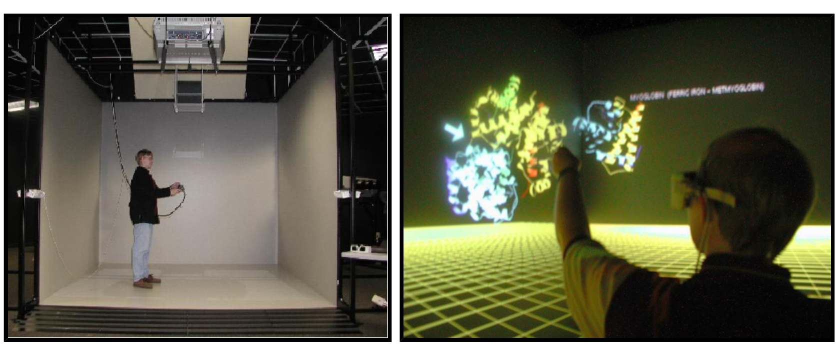

Figure 4: A CAVE-like immersive, virtual environment (COVE system at the Engineering Research Center at Mississippi State University) without and with VE.

Single-screen Projection-based Systems

Single-screen projection-based (SSPB) systems such as Fakespace System's ImmersaDesk® and the Responsive Workbench (RWB) consist of one screen, usually several feet in diameter, which is mounted at a variable angle. These Virtual Model Displays (VMDs) lack complete immersion, but guarantee excellent object presence. While the ImmersaDesk® utilizes a near-vertical pitch of the display surface, the RWB uses a tabletop metaphor, in which virtual objects appear to lie on the table's surface. This ensures easy accessibility for interaction with the data and allows intuitive interfaces to be shared by several users. The field of vision is limited by the screen dimensions, since the displayed data can be explored only by looking down and in a forward direction. No surrounding view of the environment is possible, and only small or a reasonable number of large structures fit on the screen, so that navigation in a large virtual world is not necessary. Virtual Model Displays, or laboratory table VEs, are therefore mainly employed for examination and manipulation tasks of virtual objects, where the object is within reach of the user.

Head Mounted Displays

Head Mounted Displays (HMDs) are usually deployed in augmented reality applications. Some models are mounted on full helmets, which are too heavy for long time use, while others provide displays which are mounted in a construction similar to eyeglasses. Not all HMDs support stereo viewing. They are not optimal for all virtual environments due to their limited field of view, low resolution, and limitation to a single user. Since exact synchronization is necessary, collaborative work environments usually do not employ HMDs.

Figure 5: Using a (a) Virtual Workbench and (b) a Head Mounted Display (HMD)

Tiled Projection-based Systems

Unfortunately, the resolution of most projectors is still rather limited. Therefore, multi-projector tiled displays with 9 (for 3x3 tiles) or more projectors, can provide a substantially higher resolution than conventional screens. Since several images are tiled over a single arbitrarily large display surface, overlapping areas have to be aligned [Chen et al. 2000] [Chen et al. 2002], and variation in color eliminated through luminance matching [Majumder and Stevens 2004].

Tiled LCDisplay Systems

Tiled LC panel display systems consisting of 3x3 LCDs are a space-saving alternative, but are not stereo-capable and can not compare to an immersive environment, especially since their small size and technical nature prevent their use in a surround screen setup.

Figure 6: (a) and (b) Tiled 3x3 Projector Display with 9 projectors, (c) Tiled 3x3 LCDisplay

Summary

This survey shows that the two most important properties of a display environment are:

- 3D capability, and
- Interaction space (desktop vs. large, open space).

The combination of input devices that require a table with large, immersive, open spaces in a 3-D display environment is not practical. Also, the combination of input devices that are 2D in nature with a stereoscopic display does not make use of the capabilites of the VR environment to the fullest extent possible. Input devices that can be operated in an open space with one or both hands seem to be most suitable for 3D environments. Mixed systems, such as the Responsive Workbench, combine the table-top paradigm with stereoscopic rendering. However, a 2D mouse or a joystick, even though they are desktop-based input devices, are not suitable due to their lack of support for multiple degrees of freedom, and also due to their property of constraining the user to the surface of the table or to a particular location on the table. In general, if the user task includes selecting and picking of objects, direct methods, such as grabbing using pinch gloves or dragging using a styles, are preferable over indirect methods with disconnected hand-eye movement. Depending on the shape of the input device, a cursor or pointer associated with the input device and representing a single point used for object selection has been found to be helpful in performing precise navigation tasks.

Case Study: Protein Visualization Application

The purpose of this case study is to explore various 2D and 3D interaction paradigms and their utility in analyzing the 3D structure of proteins, a task that requires 3D navigation, for example, translation in *x*, *y*, and *z*, and rotation about the *x*, *y*, and *z* axes. In addition, object selection by picking (using a push button or a similar gesture) is necessary to handle multiple objects. These tasks are typical for most applications in Virtual Reality. The protein visualization has been chosen because it is a typical example of an application where multiple renderings of an object from various angles and viewpoints may lead to new insights and a better understanding of how shape determins function. The complex 3D structure of macromolecules is directly related to their function. This relation can best be explored by generating high quality 3D visualizations and by provinding an intuitive navigation interface which allows for in depth inspection of specific details. For a close analysis of a 3D protein structure, it is necessary to position and rotate the structure freely in space, with the possibility to explore the object from every angle and at various zoom levels. Since macromolecules with similar structures often have similar functions, a comparative exploration of several related structures is required, enabling a closer examination of similarities and differences through side-by-side comparison or superimposition, which might yield important information for understanding the relation of structure and function. Detailed wireframe-like stick, ball-and-stick, or space-filling (CPK) representations provide details of the atomic structure, including information on volume, size, shape, and surface structure. Abstract schematic models can be given through so-called cartoon representations, which allow for easy identification of specific motifs consisting of β sheets (arrows), α helices (cylinders, helices), and loops (ribbons). Since the different models emphasize diverse aspects of the structure, a visualization of different representations is indespensable for a comprehensive analysis of the characteristical features of the structure and the surface of the molecule.

Figure 7: The 3D structure of the enzyme Glutamine Synthetase (2GLS) as shown on a 2D screen shot, on a tiled projection-based system and on a tiled LCDisplay.

The protein visualization application focuses on the exploration of several large molecular structures in real time in an immersive virtual environment. It allows the user to compare several complex structures side-by-side or by superimposing them, and to position each structure freely in the virtual workspace so that details that may otherwise be occluded can be revealed. This is motivated by the fact that particular perspectives or orientations of a model may not be suitable for recognition of specific features. The tasks required for a functional analysis of complex molecules are much easier achieved in VR than in commonly used, single-perspective, static or dynamic 2D projections. Since virtual objects may occlude each other so that individual objects are impossible to select by picking a specific point on the surface of the object, the interaction metaphors have to be adapted to allow for intuitive navigation. This implies that various methods for picking and moving of an object must be provided. For example, the center of rotation can be changed from the picked point to the center point of the object (or even to an arbitrary point in space), although the closer the center of rotation is to the object, the more natural and less confusing the navigation occurs to the user. In our case study, which employed various types of input devices, ranging from 2D to 3D (up to six degrees-of-freedom), we found that the input devices that are most suitable for exploring macromolecular structures are the PINCH gloves and the Rumblepad gamepad. With the PINCH gloves, touching, grabbing and moving a 3D structure that is within arms reach is very intuitive. However, the number of intuitive pinch combinations is limited, and the tracker cables and the gloves themselves are not always comfortable for the user. In our application, the gamepad proved to be the most flexible interaction device. A large number of functions and degrees of freedom can be mapped to the numerous buttons and axes according to individual preferences, and the cordless design allows for unhindered interaction in the VE. While the PINCH gloves worked best with the virtual workbench, where molecules could be placed and inspected in a virtual workspace environment and where the user could reach across the horizontal, table-like 3D display, the gamepad was suitable for all display environments with vertically and horizontally mounted screens. We did not test the interaction devices with the head-mounted display (HMD), since due to its low resolution and limited field of view, this display device is not suitable for our protein visualization application. The choice of the display depends on the specific requirements of the navigational tasks. A fully immersive VE like the CAVE is convenient for collaborative exploration tasks conducted by small user groups,

who want to be able to walk around 3D structures, and to inspect details of an object in close-up views. Only by total immersion can the user experience the full extent of the complex 3D structure of a protein. Newer, tiled displays provide a much higher resolution for a clearer and more exact rendering of fine details. Not all of them are stereo-ready yet and therefore not capable of providing complete immersion. High-resolution displays are, of course, desirable, but not always affordable. As a work-around and also to provide more flexibility, zooming in on single structures and specific details is essential, since models can be too complex and overloaded with detail to allow substantial visual analysis on a display with low resolution. 3D is a good solution to overcome screen clutter, even though the number of pixels on the screen is similar to 2D displays. By adding a third dimension, objects of lower priority can be pushed in the background, eliminating the ambiguity of the zoom operation on a 2D display (size vs. distance).
The lesson learned from this comprehensive case study was that it is necessary to match a high-quality display device with suitable input device technology. A high-resolution, stereoscopic display cannot overcome the limitations of a poor input device to facilitate precise navigation tasks. Both input and display devices go together in enabling the user to complete a navigation task in a virtual environment in an intuitive way and with high precision.

Conclusions and Future Work

We have presented an overview of applicable input devices and display systems for the exploration of protein structures in virtual environments in real time. The purpose of the study was to provide a survey of existing input and display devices and to draw conclusions with respect to their utility in various combinations. The survey of input devices lead to the conclusions, which provide guidelines that can be helpful in the design of future input devices. The survey of display devices mainly showed limitations of current display devices and emphasizes that increased pixel resolution and - for many applications - 3D readiness should be a design goal for new, large-scale displays.
In the future, ubiquitous computing and large-screen display environments will become more commonplace. New, emerging technologies such as high resolution projector displays, flat-panel displays, and OLED displays, will make it possible to access information everywhere and anytime. Interactive navigation using 2D and 3D input devices will be a critical component of this development.

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